Residential Energy Consumption Controlling Techniques to Enable Autonomous Demand Side Management in Future Smart Grid Communications

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***Abstract*—This paper presents an overview of home appliances scheduling techniques to implement demand side management in smart grid. Increasing demand of consumers have affected the power system badly as power generation system faces a number of challenges both in quality and quantity. Economical generation and efficient consumption can solve this problem in future smart grid as it is integrated with information and communication technologies. Smart grid has opportunities to employ different pricing schemes which help also in increasing the efficiency of appliances scheduling techniques. Optimal energy consumption scheduling minimizes the energy consumption cost and reduces the Peak-to-Average Ratio (PAR) as well as peak load demand. In this work, we discuss different energy consumption scheduling schemes that schedule the household appliances in real-time to achieve minimum energy consumption cost and reduce peak demand to shape the load curve.**

***Index Terms*—Demand side management, optimal energy consumption scheduling, peak load demand, smart grid.**

I. Introduction

A system that implements communication and information technology in electrical grid is known as smart grid. Smart grid system gathers information about the activities of electrical energy suppliers and users. Smart grid improves the customers' load utilization by deploying the communication based monitoring and controlling architectures [1]. With the addition of different types of new loads e.g. Plug-in Hybrid Electric Vehicles (PHEVs), the normal residential load has potentially increased. Hence it is very important to develop new methods for peak load reduction. There are some environmental issues related to current power systems. Some countries widely use the oil and coal fired power plants to meet the peak demands, as a result a huge amount of CO_2 and green house gases is emitted. Smart grid enables Demand Side Management (DSM) to overcome these problems. DSM was proposed in the late 1970s [2]. DSM monitors, plans and implements those utility functionalities that are designed to encourage low consumption by the consumers during peak hours in order to shape the utility load curve. DSM programs are implemented to exploit better utilization of current available generating power capacity without installing new power generation infrastructure [3]. DSM programs facilitate users to shift loads from peak hours to off peak hours to reduce the peak load [4]. Worldwide energy utilization in buildings is approximately 40% of global power consumption [5]. Currently, consumption of electricity in buildings is not efficient and is leading towards the wastage of billions of dollars and huge amount of green house gas emission. Better utilization of energy consumption in buildings is an important issue. Heavy loads run in the peak hours due to which utility load curve potentially goes high. DSM controls the residential loads by shifting the load from peak hours to off-peak hours in order to reduce the peak load curve and improve energy efficiency by scheduling the energy consumption.

In previous literature, various load management techniques have been discussed to enable autonomous DSM in future smart grid. Incentive based energy consumption controlling schemes are discussed in [6], [7], [8], have explained a Direct Load Control (DLC) scheme for residential load control to enable demand side management. In [9], a home energy consumption scheduling technique is elaborated which uses Energy Management Controllers (EMCs) for scheduling the appliances. [10], has presented a priority based scheduling scheme, in which the appliance that has higher priority according to load curve, switched ON first without any restriction. Low priority devices are switched ON with some delay. Different home energy management schemes in future smart grid are discussed in [11]. The home energy management schemes are combined with different pricing schemes in order to make the schemes more efficient e.g. a day ahead pricing has been used in energy management scheme to minimize the electricity charges of a consumer [12].

Our work focus on different energy consumption scheduling schemes to meet the peak load demand and to reduce the monetary cost. These residential load controlling schemes are based on optimization and different scheduling criteria. Scheduling of appliances involves different pricing schemes. By scheduling the appliances, heavy loads are shifted from peak-hours to off-peak hours according to their energy consumption profile. In this way, peak-hours load is reduced by controlling the appliances.

Rest of the paper is organized as follows: Section II describes different scheduling schemes for demand side management. In Section III, we conclude this paper.

II. Different Scheduling Schemes for DSM

Efficiency of power consumption is an important factor. Now a days customers expectations are increasing both in

978-0-7695-5093-0/13 $31.00 © 2013 IEEE
DOI 10.1109/BWCCA.2013.94

quality and quantity. Due to limited energy assets and expensive process of integrating new energy resources, there is an important need to improve our system power utilization. Energy efficiency refers to using minimum energy to provide the same or improved level of service to the energy consumer in an economically efficient way. It includes using minimum energy at any time, including during peak periods. Smart grid implements advance metering infrastructure for the load prediction in residential areas and improves energy efficiency [13]. To achieve high reliability in electric grid utility companies need to reduce the peak load demand. To avoid the peak condition in the grid, domestic and industrial devices such as air conditioners, refrigerators and heater are shifted to off peak hours.

In future smart grid, both power companies and users can take advantage from economical and environmental aspects of smart pricing models [3]. Consumer's energy demand increase during peak hours. Utility companies run peaker power plants to meet this peak demand during peak hours. Peaker plants charge higher prices per kilo watt hour. Communication and metering technologies enable smart devices in homes to reduce peak load demand during high cost peak hours. Electricity prices are high during peak hours and low during off peak hours. Therefore consumers avoid high price peak hours and shift their heavy loads to off peak hours. General approach for the management of energy consumption in buildings is shifting consumption and reducing consumption. Smart grid applies DSM to cope with energy consumption cost. Energy consumption cost can be minimized in homes by shifting the high load from peak hours to off peak hours.

In previous literature, following techniques have been proposed to minimize the peak load in peak hours and monetary cost.

A. An Autonomous Three Layered Structure Model for DSM

In [2], a scheduling model has been presented in which a layered structure consisting of three modules for Admission Control (AC), Load Balancer (LB) and Demand Response Manager (DRM) are used to control the peak load demand. The model of this scheme is shown in Fig.1 [2]. Loads are divided into three different categories based on their load characteristics for the minimization of peak load demand.

Baseline load is the power consumption of those appliances that must be run immediately at any time. Baseline load includes lighting, cooking rang and networking devices etc.

Burst load is the load that is ON for a fixed duration and starts and stops within the given dead line e.g., washing machine, dish washer and dryer.

Regular load is related to appliances that are always in running state during a long period, such as refrigerator, water heater and Heating Ventilation and Air Conditioning) (HVAC) of house.

The key role of run-time scheduling of appliances is to meet the power capacity limit while satisfying different capacity criteria e.g. comfort level of domestic users. Present architecture controls the appliances using online scheduling approach in the run-time manner.

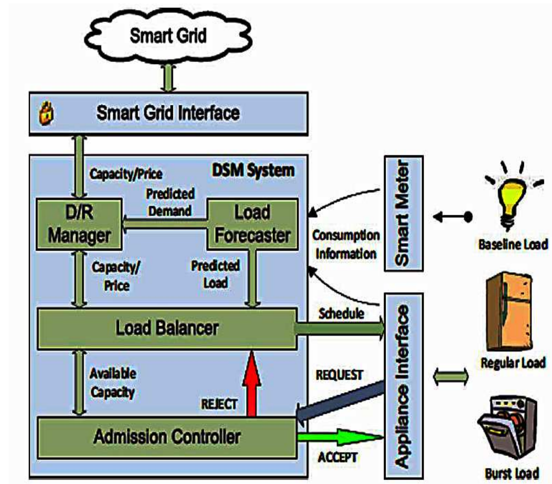

Fig. 1. Three layered architecture for load management on demand side

In previous literature, many algorithms have been used for run time scheduling, most popular are Least Slack Time (LST), Earliest Deadline First (EDF), Bratley and Spring. Spring algorithm is used for scheduling in AC module. AC manages the requests at run time coming from smart appliances and information received from smart meter. AC module is time triggered and performs adequate load scheduling. It accepts some requests based on priority (available capacity and power request) and rejects the rest. The appliances, whose requests are accepted by AC, start their operation immediately while rejected requests of appliances are forwarded to LB. The search space for scheduling the appliances in different time slots is driven by heuristic function H. At each stage of search space, the heuristic function H is applied to tasks one by one that has to be scheduled. The task with least value specified by heuristic function called heuristic value is elected to further extend the current schedule. In this case the heuristic value is scaled between 0 & 1, which represents the priority of the task. For example, appliances such as water heater and refrigerator will have 1 heuristic value when the desired temperature is attained and 0 when the temperature is within the specified limit called comfort zone. LB schedules the tasks whose requests are rejected from AC. LB evenly distributes the electrical load of appliances over a time frame and schedules the requests that have been refused by AC. To minimize the total energy cost, a Mixed Integer Programming (MIP) problem is solved. Therefore LB minimizes the cost function analogous to energy price. In different circumstances of considered appliances, LB establishes an appropriate schedule that would evenly distribute the appliances load over a time horizon. In such a way, AC and LB schedule the appliances on run time with respect to limited capacity constraints and overall peak load and energy consumption cost is minimized.

B. Backtracking-based Technique for Load Control

A task model is presented in [14] to schedule the home appliances for reducing the local peak load as well as the global peak for effective DSM. The task model is shown in Fig.2 [14].

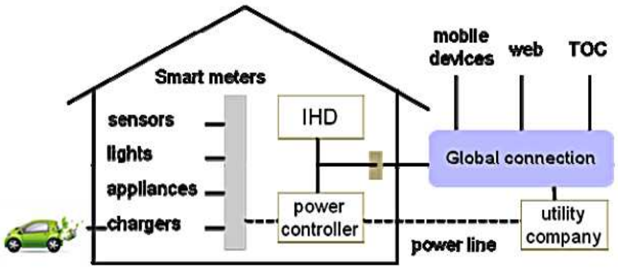

Fig. 2. Power scheduler operation

Presented scheme designs a power scheduler that is capable of minimizing peak load in buildings. This model consists of actuation time, operation length, dead line and consumption profile.

The proposed task model schedules the appliances in real time. Electric devices are designed as tasks having starting time, execution time and deadlines. Task T_i can be designed by following parameters: F_i shows that whether T_i has preemptive operation or non-preemptive. A_i is activation time of task, D_i is deadline and U_i illustrates the operation length. Operation of non-preemptive task can start from its activation time A_i to the latest start time (D_i-U_i). For preemptive task, device activation time must be picked from U_i out of (D_i-A_i) time slots. Backtracking optimization technique is used for scheduling the appliances. Backtracking additionally frame a search tree on the allocation table. Scheduler copies the profile entry of different appliances one by one according to task profile to the allocation table. This potential search tree consists of all feasible solutions including worthless solutions. At each intervening node, which passes to a feasible solution, it checks whether the node can guide to a feasible solution. If it cannot, remaining sub tree is reduced. Otherwise iteration proceeds to the next level. By this phenomenon, scheduler searches the feasible time slots to schedule the appliances. Optimal scheduling of appliances reduces the peak load curve and also reduces the energy consumption cost. This model reduces the peak load up to 23.1%.

C. Game-Theoretic Based DSM

In [15], a game-theoretic model based optimization technique is discussed to schedule the energy consumption of appliances. In this model users are players and their strategies are their daily scheduling loads. Optimal performance in terms of energy cost minimization is achieved at Nash equilibrium of energy scheduling game. The model considers a common scenario where a single utility company serves different users. This model systematically manages the appliance schedule and shifts them in order to reduce energy cost. Energy Consumption Scheduler (ECS) is deployed in smart meters for scheduling the household appliances. ECS uses a distributed algorithm to find the feasible schedule for each user. A smart power system with only one energy source and multiple consumers has been assumed. This scheme considers two types of appliances, shiftable and non-shiftable. Shiftable appliances e.g., PHEVs, washing machine and dryer. Non-shiftable appliances are those that are always in operating state for a long time period e.g. fridge and lights. ECS only schedules the shiftable appliances. The operation of ECS is presented in Fig.3 [15]. In this technique, scheduler manages

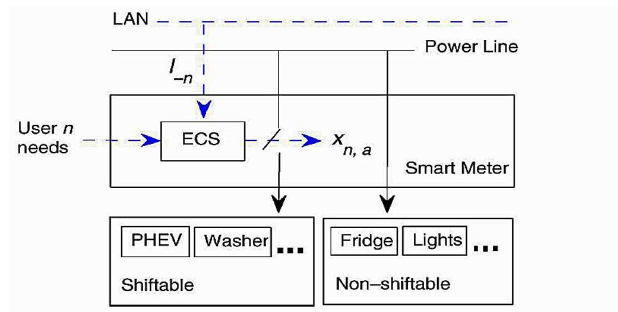

Fig. 3. Model with ECS devises deployment

and shifts the appliances energy consumption for appropriate scheduling. Consider each user $n \in N$, let A_n denote set of appliances. An energy consumption scheduling vector for appliance $a \in A_n$ can be defined as:

$$X_{n,a} \triangleq [x^1_{n,a}, \cdots, x^H_{n,a}] \tag{1}$$

Where

$x^h_{n,a}$: Energy consumption of appliance a scheduled for 1 hour from user n.

ECS function decides optimal choice for energy consumption vector $X_{n,a}$. Each appliance is scheduled according to its daily predetermined energy consumption that is:

$$\sum_{h=\alpha_{n,a}}^{\beta_{n,a}} x^h_{n,a} = E_{n,a} \tag{2}$$

And

$$x^h_{n,a} = 0, \forall h \in H \backslash H_{n,a} \tag{3}$$

Where

$E_{n,a}$: Predetermined daily energy consumption of appliance a.
$\alpha_{n,a}$: Interval starting time that appliance consumption can be scheduled.
$\beta_{n,a}$: Interval end time that appliance can be scheduled.
$H_{n,a} \triangleq [\alpha_{n,a}, \cdots, \beta_{n,a}]$

Appliance minimum standby power level is defined by $\gamma^{min}_{n,a}$ and maximum power level by $\gamma^{max}_{n,a}$. Finally feasible scheduling set for the appliances of user n is acquired as follows:

$$\chi_n = \{X_n | \sum_{h=\alpha_{n,a}}^{\beta_{n,a}} x_{n,a}^h = E_{n,a}, x_{n,a}^h = 0, \forall h \in H \backslash H_{n,a},$$
$$\gamma_{n,a}^{min} \leq x_{n,a}^h \leq \gamma_{n,a}^{max}, \forall h \in H_{n,a}\} \quad (4)$$

This feasible schedule is only valid for $x_n \in \chi_n$. Simulation results show that with the deployment of ECS function in smart meters, PAR reduces up to 17% and cost reduces up to 18% as presented in Fig.4 and Fig.5 [15].

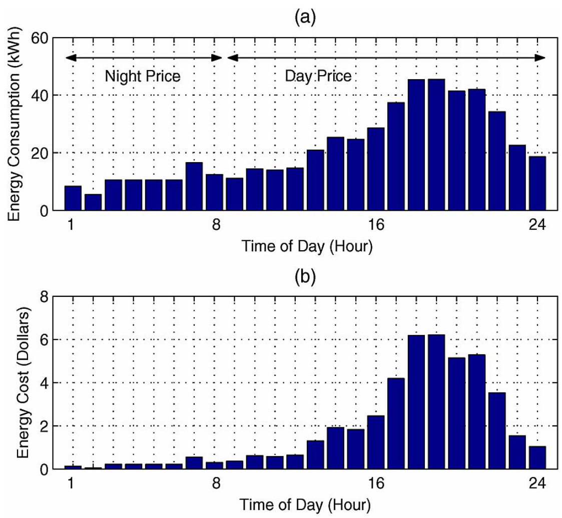

Fig. 4. When ECS not deployed (PAR is 2.1 and the total daily cost is \$44.77)

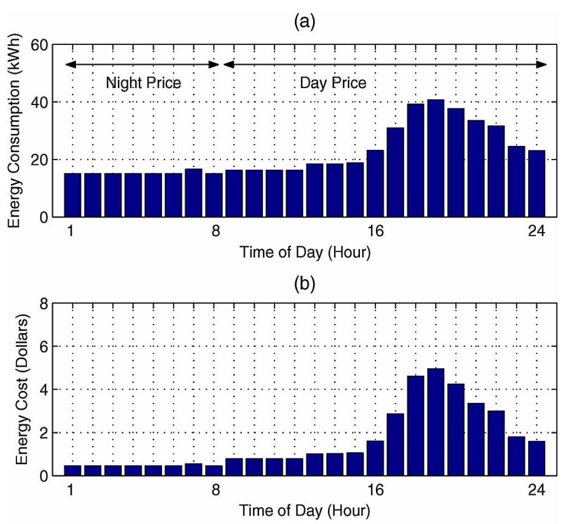

Fig. 5. When ECS not deployed (PAR is 1.8 and the total daily cost is \$37.90)

D. ECS Device Based Scheduling

In [16], an energy consumption scheduling (ECS) device based scheduling technique is discussed. In this technique, authors consider a scenario of power system where an energy source (e.g., a generator is connected to electric grid) is shared by different users. Each user is equipped with an ECS device in the smart meter shown in Fig.8 [16]. Assume that each user

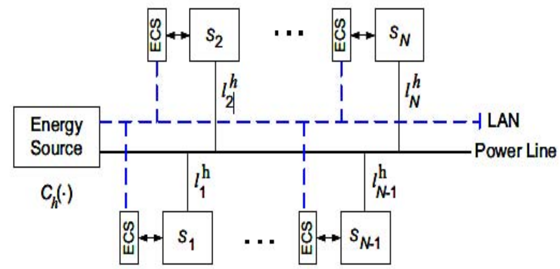

Fig. 6. Smart grid system model with N load subscribers

is facilitated with smart meter. In this scheme, deployment of ECS devices in smart meters enables autonomous DSM. ECS devices are equipped in smart meters connected with each other. These devices are also connected with power grid and local area network to communicate with the smart grid infrastructure. Distributed algorithm is used to schedule the optimal energy consumption for each subscriber. According to individual energy needs of all subscribers ECS devices schedule the energy consumption of household appliances. ECS devices are interrelating automatically by running an algorithm to find an optimal schedule for energy consumption of each subscriber. This algorithm reduces the total energy cost and shape the load curve in peak hours. By subscribing this algorithm in smart meters, all users pay minimum amount of utility bills to the utility company as shown in Fig.6 [16].

A new pricing scheme is also introduced for this model which is developed from game theoretic model, to reduce the total cost. Simulation results are demonstrated in Fig.7 and Fig.8 [16]. Simulation results show that ECS devices efficiently schedule the appliances energy consumption in the whole day.

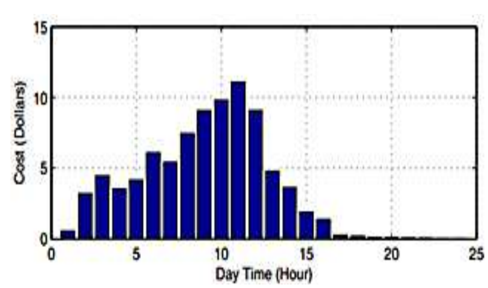

Fig. 7. Daily cost \$86.47 (ECS devices are not used)

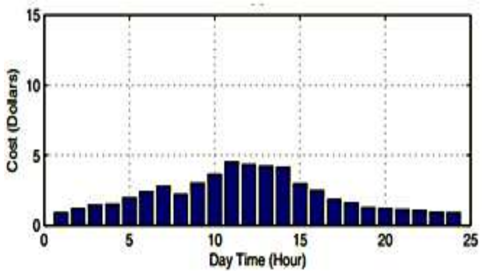

Fig. 8. Daily cost $53.81 (ECS devices are deployed)

E. An Optimal and Autonomous Residential Load Control Scheme

Smart pricing models in future smart grid can potentially benefit both users and utility companies regarding the economical and environmental advantages. In [17], an automatic and optimal energy consumption scheduling scheme is discussed to minimize the PAR and reduce the waiting time of each appliance operation in household. For optimal scheduling of appliances, residential load controller requires the capability to predict the prices in real time. In this scenario, real-time pricing and inclining block rates are combined to balance the load and minimize PAR. An ECS device is deployed in residential smart meters to control the load of household appliances. Fig.9 [17], shows the function of smart meter in this scheme.

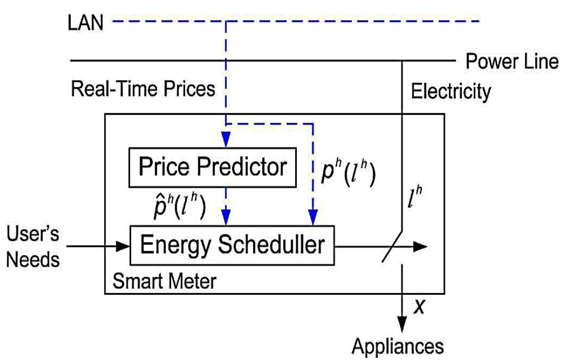

Fig. 9. Smart meter operation in this scheme

When load demand is high in peak hours, a request is sent by smart grid to smart meters to reduce the load. In this case, scheduler takes action and increases the upcoming prices of next 2 or 3 hours by optimization technique. Therefore, some portion of load automatically suspends and reduces the total load. Price predictor and energy scheduler are two main units to control the residential load. Price predictor estimates the upcoming prices and allows scheduler to schedule the appliances according to user's need.

F. Vickrey-Clarke-Groves (VCG) Mechanism Based DSM

Vickrey-Clarke-Groves (VCG) mechanism in [18], maximizes the social welfare i.e. the difference between aggregate utility function of all users and total energy cost. Authors consider that each user deployed Energy Consumption Controller (ECC) device in its smart meter for scheduling the household appliances. ECC schedules the household appliances on runtime. VCG mechanism develops the DSM programs to enable efficient energy consumption among all users. In this scheme, each user provides its energy demand to the utility. By deploying a centralized mechanism in ECC device, the energy provider estimates each users optimal energy consumption level and declares particular electricity payment for each user. In this way, VCG mechanism reduces the energy cost. Load demand can be divided into two types i.e. must-run loads and controllable loads. Must-run loads e.g. a refrigerator that is always in ON state during the whole day. The controllable loads are the appliances where operation can be stopped, shifted and accommodated in different time slots according to demand. For optimal solution, we evolve an optimization problem to reduce the total energy cost charged on energy provider while maximize aggregate utility functions of all users. The solution of following optimization problem provides an efficient energy consumption schedule for user's energy consumption in order to reduce the cost.

$$\underset{x_n \in X_n, \forall n \in N}{\text{maximize}} \sum_{n \in N} U_n(\sum_{k \in K} x_n^k) - \sum_{k \in K} C_k(\sum_{n \in N} x_n^k) \quad (5)$$

Where

X_n Power consumption vector of user n
$U_n(\cdot)$ Utility function of user n
$C_k(\cdot)$ $C(L_k) = a_k L_{k^2} + b_k L_k + C_k$
$C_k(L_k)$ Cost function of L_k energy units offered by utility in each time slot k.

G. A Scheme for Tackling Load Uncertainty

In [19], an optimization based residential load controlling algorithm is proposed that tackles the load irregularity to reduce energy cost in real-time. In algorithm, it is assumed that each user is facilitated with smart meter. Each smart meter is equipped with ECC unit. ECC unit schedules and manages the household energy consumption. In this scenario both real-time and inclining block rate prices strategies are combined. Proposed algorithm is formulated as an optimization problem. Appliances are divided into following categories must run and controllable loads. Must-run loads start operation immediately at any time e.g. Personal Computer (PC), TV. These loads start operation without the interruption of ECC unit. Controllable appliances operation can be interrupted or delayed.

We separate the operation cycle of appliance into time slots denoted by T. Each time slot activate with the phase of admission control. For the starting of appliance operation, admission control sends an admission request to ECC unit. Once request is endured, appliance state changes from sleep to awake. Appliance request acceptance depends on its operation schedule specified by ECC unit. ECC unit implements a centralized algorithm and determines the optimal appliances schedule in each time slot. This centralized algorithm is based on an optimization problem formulated for appliances schedule under different constraints.

TABLE I
Comparison of different Energy consumption controlling schemes

Scheme Name	Method	Load Minimization	Cost Minimization	Scheduling	Pricing	Coverage
A Model for Autonomous DSM	Load control scheduling model	66.66%	NA	Real-time	CPP,TOU,RPP	Local
Backtracking Based Technique	Back-tracking based scheduling	23.1%	NA	Real-time	RTP	Local
Game Theoretic Model	Game theoretic pricing & scheduling	17%	18%	Run time	Proportional to daily load & generation cost	Neighbor-hood
ECS Device Based Scheme	Energy consumption scheduling	38%	37%	Run time	Proportional to daily load & generation cost	Neighbor-hood
Optimal Residential Load Control Scheme	LP-Based optimization	22%	10-25%	Run time	RTP	Local
Vickrey-Clarke Groves Mechanism	Scheduling and Optimization	38%	37.8%	Run time	VCG pricing scheme	Neighbor-hood
Scheme for Tackling the Load Uncertainty	Optimization based algorithm and scheduling	25.5%	NA	Real time	RTP & IBR	Neighbor-hood

III. Conclusion

In this paper, we have compared different residential load controlling techniques in the smart grid. Residential load controlling techniques are employed for efficient consumption of electricity in residential buildings like homes and offices. In current power grid, the load demand curve shows that there is huge difference between the demand of peak hours and off-peak hours. The utilities want the load curve to be nearly smooth to avoid the operation of peaker plants. The load controlling techniques shift some specific load from peak hours to off-peak hours and hence helps in making the demand curve smooth. These techniques reduce the energy consumption cost and minimize PAR as well as peak load. Consumer should also be encouraged to schedule the appliances according to schemes discussed in the paper. Table I shows the comparison of different schemes. Scheme I reduces the peak load up to 66.66%. So this model is more efficient. ECS device based scheme and VCG mechanism minimize the cost up to 37%.

References

[1] Javaid, Nadeem, et al. “Monitoring and Controlling Power using Zigbee Communications.” Broadband, Wireless Computing, Communication and Applications (BWCCA), 2012 Seventh International Conference on. IEEE, (2012).

[2] Costanzo, Giuseppe Tommaso, et al. “A system architecture for autonomous demand side load management in smart buildings.” (2012): 1-9.

[3] Photovoltaics, Dispersed Generation, and Energy Storage. “IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads.” (2011).

[4] Martins, Rodrigo, and Felipe Meneguzzi. “A Smart Home model to Demand Side Management.” (2013).

[5] M. N. Ullah, A. Mahmood, S.Razzaq, M. Ilahi, R.D. Khan, N. Javaid, “A Survey of Different Residential Energy Consumption Controlling Techniques for Autonomous DSM in Future Smart Grid Communications”, J. Basic. Appl. Sci. Res., 3(3)1207-1214, (2013).

[6] Caron, Stphane, and George Kesidis. “Incentive-based energy consumption scheduling algorithms for the smart grid.” Smart Grid Communications (SmartGridComm), 2010 First IEEE International Conference on. IEEE, (2010).

[7] Ruiz, Nerea, Iigo Cobelo, and Jos Oyarzabal. “A direct load control model for virtual power plant management.” Power Systems, IEEE Transactions on 24.2 (2009): 959-966.

[8] Wu, Qiuwei, Peng Wang, and Lalit Goel. “Direct load control (DLC) considering nodal interrupted energy assessment rate (NIEAR) in restructured power systems.” Power Systems, IEEE Transactions on 25.3 (2010): 1449-1456.

[9] Costanzo, Giuseppe T., Jan Kheir, and Guchuan Zhu. “Peak-load shaving in smart homes via online scheduling.” Industrial Electronics (ISIE), 2011 IEEE International Symposium on. IEEE, (2011).

[10] Rossello Busquet, Ana, et al. “Reducing Electricity Demand Peaks by Scheduling Home Appliances Usage.” (2011): 156-163.

[11] I. Khan, A. Mahmood, N. Javaid, S.Razzaq, R.D. Khan, M. Ilahi, “Home Energy Management Systems in Future Smart Grids”, J. Basic. Appl. Sci. Res., 3(3)1224-1231, (2013).

[12] F. Baig, A. Mahmood, N. Javaid, S. Razzaq, N. Khan, and Z. Saleem, “Smart home energy management system for monitoring and scheduling of home appliances using zigbee,” (2013).

[13] Anas, M., et al. “Minimizing Electricity Theft using Smart Meters in AMI.” P2P, Parallel, Grid, Cloud and Internet Computing (3PGCIC), 2012 Seventh International Conference on. IEEE, (2012).

[14] Lee, Junghoon, et al. “Energy consumption scheduler for demand response systems in the smart grid.” Journal of Information Science and Engineering 28.5 (2012): 955-969.

[15] Mohsenian-Rad, A., et al. “Autonomous demand-side management based on game-theoretic energy consumption scheduling for the future smart grid.” Smart Grid, IEEE Transactions on 1.3 (2010): 320-331.

[16] Mohsenian-Rad, A-H., et al. “Optimal and autonomous incentive-based energy consumption scheduling algorithm for smart grid.” Innovative Smart Grid Technologies (ISGT), 2010. IEEE, (2010).

[17] Mohsenian-Rad, A-H., and Alberto Leon-Garcia. “Optimal residential load control with price prediction in real-time electricity pricing environments.” Smart Grid, IEEE Transactions on 1.2 (2010): 120-133.

[18] Samadi, Pedram, et al. “Advanced demand side management for the future smart grid using mechanism design.” Smart Grid, IEEE Transactions on 3.3 (2012): 1170-1180.

[19] Samadi, Pedram, et al. “Tackling “the” “Load” Uncertainty Challenges for Energy Consumption Scheduling in Smart Grid.” (2013): 1-10.